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A lumped-parameter dynamical model of a nuclear heating reactor cogeneration plant

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ABSTRACT

Based on the conservation laws of mass, energy and momentum, a lumped-parameter dynamical model is proposed for the nuclear heating reactor cogeneration plant NHR200-II that can be served for electricity production and district heating. This model is mainly composed of the dynamics of the reactor, steam generator, turbine, deaerator, heat exchangers and secondary steam flow network. Then, the steady and transient validation of this lumped-parameter model are given based on the comparison between the parameter values given by this model and the model for plant design, which shows that both the steady and transient errors are acceptable, and which further reveals that the thermal resistances and capacities of this model are properly given. Finally, the open-loop responses under different exterior disturbances such as reactivity and coolant flowrates as well as the closed-loop responses under the cases of power ramp and switch are all given by the numerical simulation software developed based upon this newly-built lumped-parameter model for NHR200-II plant, where the rationality of the responses are analyzed from the viewpoint of plant physics and thermal-hydraulics. This model can be utilized for not only the control system design but also the development of a real-time simulator for the hardware-in-loop verification of control systems.

1. Introduction

Nuclear fission energy is a typical clean base-load energy resource [1], which may substitute the fossil in a centralized way and in a great amount, can be applied for electricity generation, for process heat production and also for building hybrid energy systems (HESs) through coupling with the renewables such as the solar and wind [2,3]. After the introduction of commercial nuclear fission reactors in the late 1950s, the individual nuclear power unit has increased from tens of megawatts of electricity to around 1600MW_e, whose main reason is the consideration on "economy of scale" [4]. The grow-up of reactor size, which leads to a high power density, not only improved the economic competitiveness relative to the fossil plants but also induced the complex operational issues that began to moderate the industry's confidence on plant safety. More stringent nuclear safety requirements were then imposed, which induced a layering of redundant safety and auxiliary systems, and further resulted in the rapidly increasing costs, licensing periods, construction delays and operational complexity. After the severe nuclear accidents, i.e. Three Mile Island, Chernobyl and Fukushima, the safety issues of nuclear reactors become much more significant than before. Thus, the route of developing nuclear fission energy relies on "economy of scale" have to be reconsidered, and there should be reactor designs providing a satisfactory tradeoff between safety and economics.

Since the high reactor power density intensify the complexity of the plant equipment and its operation, a natural way is to decrease the reactor power density so that the decay heat can be removed inactively, and for light water reactors (LWRs), even the primary-circuit natural circulation is able to transfer the fission power to the conventional island. This leads to the development of small modular reactors (SMRs), which are defined to be fission reactors with electrical power less than 300MW_e [4–7]. Usually, SMRs have the features of low power density and relatively large heat capacity, which induces the virtues such as high system simplicity and strong safety. Some SMRs even have the inherent safety feature which prevents them from the hazards of core-melting, radiological release and LOCA (Loss of Coolant Accident). Furthermore, SMRs can offer simpler, safer and standardized modular design by

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being factory built, requiring smaller initial capital investment, and having shorter construction period, and could be beneficial in providing electricity to remote areas without transmission or distribution infrastructure, in generating local power for a large population center and in being viable for specific applications such as heat sources for the industrial complexes [4,5]. SMRs have already been seen as an important developing trend in nuclear energy industry. Many SMR designs have been proposed, where the primary coolant are usually adopted to be light-water, liquid metal/sault and gas [4–7]. The light-water cooled thermal SMR are usually called integral pressurized water reactor (iPWR), and the IRIS, NuScale and mPower designed by U.S. and the SMART designed by Korea are all typical iPWR designs with the strong safety features such as natural circulation and self-pressurization. Liquid cooled SMRs are usually small fast reactors such as the 4S (Super-Safe, Small and Simple) design by Toshiba which is fueled with enriched uranium or plutonium and is cooled by sodium. The modular high temperature gas-cooled reactor (MHTGR) (such as HTR-MODULE designed by Germany, MHTGR designed by U.S. and HTR-PM designed by China), which uses helium as coolant and graphite as both moderator and structural material, is a typical gas-cooled with inherent safety feature. The two-modular MHTGR-based HTR-PM plant is now under construction and commissioning in China Shandong Shidao Bay [8]. Nuclear heating reactor (NHR) is also a typical iPWR developed by the institute of nuclear and new energy technology (INET) of Tsinghua University, which has the key inherent safety features such as the integral arrangement of primary circuit, full power range natural circulation, self-pressurization and built-in hydraulically driven control rods [9–13]. The design of NHR started in China since early 1980s, and the first NHR, i.e. 5MW$_{th}$ nuclear heating test reactor (NHR-5) began to be built in INET in March 1986, and can be operated at full power-level since December 1989, and was then used for experiments of electricity generation, district heating and air conditioning [9–12]. Based on NHR-5, a 200 MW$_{th}$ nuclear heating reactor NHR-200 was designed, which can server for district heating, air conditioning and seawater desalination [13–15]. Moreover, on the basis of NHR200 design, a nuclear heating reactor NHR200-II with a thermal power of 200MW$_{th}$ is developed by INET very recently, whose the primary coolant pressure and temperature are increased to be much higher than NHR200, and which can not only improve the plant efficiency but also lead to the feasibility for industrial steam supply.

Plant control is crucial in guaranteeing operational safety, stability and efficiency of all those power plants based on the fossil, nuclear and renewables. Furthermore, for the design and verification of plant control system, it is necessary to build a plant dynamical model with satisfactory accuracy and validity. There have been some meaningful works on the dynamical modeling of different types of power plants or plant equipment [16–30] based on the conservation laws of mass, momentum and energy. For the dynamical modeling of equipment, the model of heat exchangers and microturbines for control system design and validation were proposed in Refs. [16,17]. For dynamical modeling of the coal-fired power plant, a simple lumped parameter dynamical model is proposed for an ultra-supercritical coal fired once-through boiler-turbine unit [18]. For dynamical modeling of the pressurized water reactor (PWR) plant, Han gave a lumped parameter model for plant thermal-hydraulic loops [19], Fazekas et al. gave a simple dynamical model of the primary circuit of VVER plant for control system design [20], Zhao et al. developed the nodal dynamical model and the corresponding simulation platform for AP1000 reactor [21,22]. For dynamical modeling of iPWRs, the lumped parameter dynamical model of the NuScale reactor has been systematically developed and verified [23,24]. For dynamical modeling of the MHTGR-based nuclear steam supply system (NSSS), Li et al. gave a simple dynamical model for MHTGR [25] and a three-sectional movable boundary model for a helical-coil once through steam generator (OTSG) [26], Dong gave a nodalized MHTGR model [27] and a simplified two-sectional OTSG model that can be utilized for dynamical simulation in the cases of both power operation and plant startup [28], moreover, Ablay proposed a very simple plant model mainly coupled by an MHTGR and a helium gas turbine [29].

NHR200-II can be applied for cogeneration of electricity and process heat, which requires the ability of power maneuvering and the flexibility of load device switching that highly rely on the plant control. Therefore, it is very important to develop the dynamical model of NHR200-II based plant, and analyze the open-loop and closed-loop dynamical behavior. In this paper, based on the conservation laws of mass, energy and momentum, a lumped-parameter dynamical model is proposed for a NHR200-II cogeneration plant served for electricity production and district heating, which is mainly composed of the dynamical models of NHR200-II reactor, U-tube steam generator (UTSG), steam turbine, moisture separation reheater (MSR), deaerator and heat exchangers. The steady and transient verification of this newly-built model is given by comparing the parameter steady and transient values given by this model and the model for plant design. Moreover, to show the dynamical characteristics of NHR200-II plant, both the open-loop responses under different exterior disturbances and closed-loop responses of power ramp and switch are given. Unlike those models based on commercial software, this model is simple enough for the development of real-time simulator, which is the basis of performing the hardware-in-loop test for digital control system verification. Moreover, since this model is composed of multiple ordinary differential equations (ODEs), it can be tuned and adjusted based on the operational data by system identification methods.

2. Description of NHR200-II cogeneration plant

To achieve the strong nuclear safety and economic viability, NHR200-II is designed with a number of advanced and innovative features such as primary circuit integral arrangement, full power range natural circulation, self-pressurization and built-in hydraulic control rod system, where the fundamental design criteria is that the reactor core should be always covered by coolant. No off-site emergency actions such as evacuation, sheltering and decontamination are the general safety requirement in case of all credible

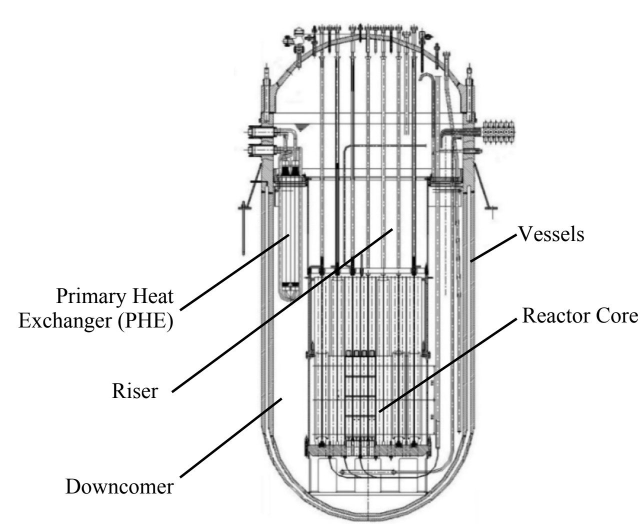

Fig. 1. Structure of NHR200-II reactor.